

# *Wireless Beyond the Third Generation— Facing The Energy Challenge*

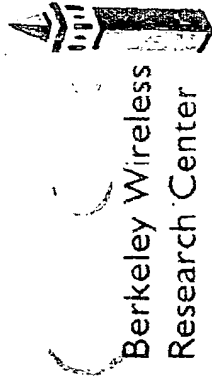
Jan M. Rabaey

BWRC

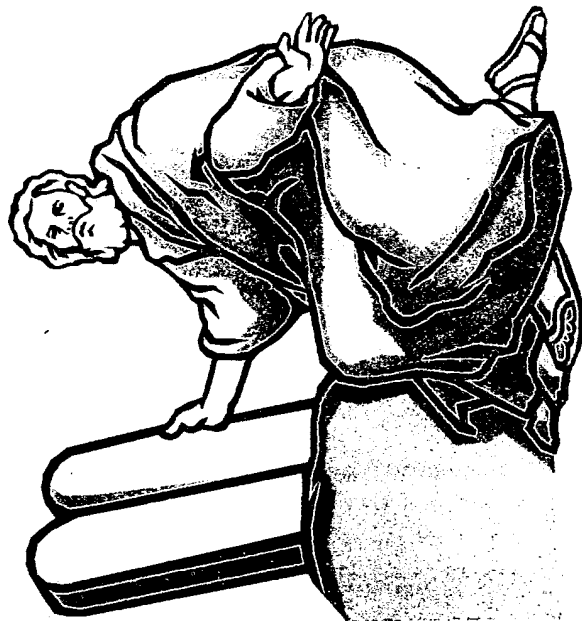
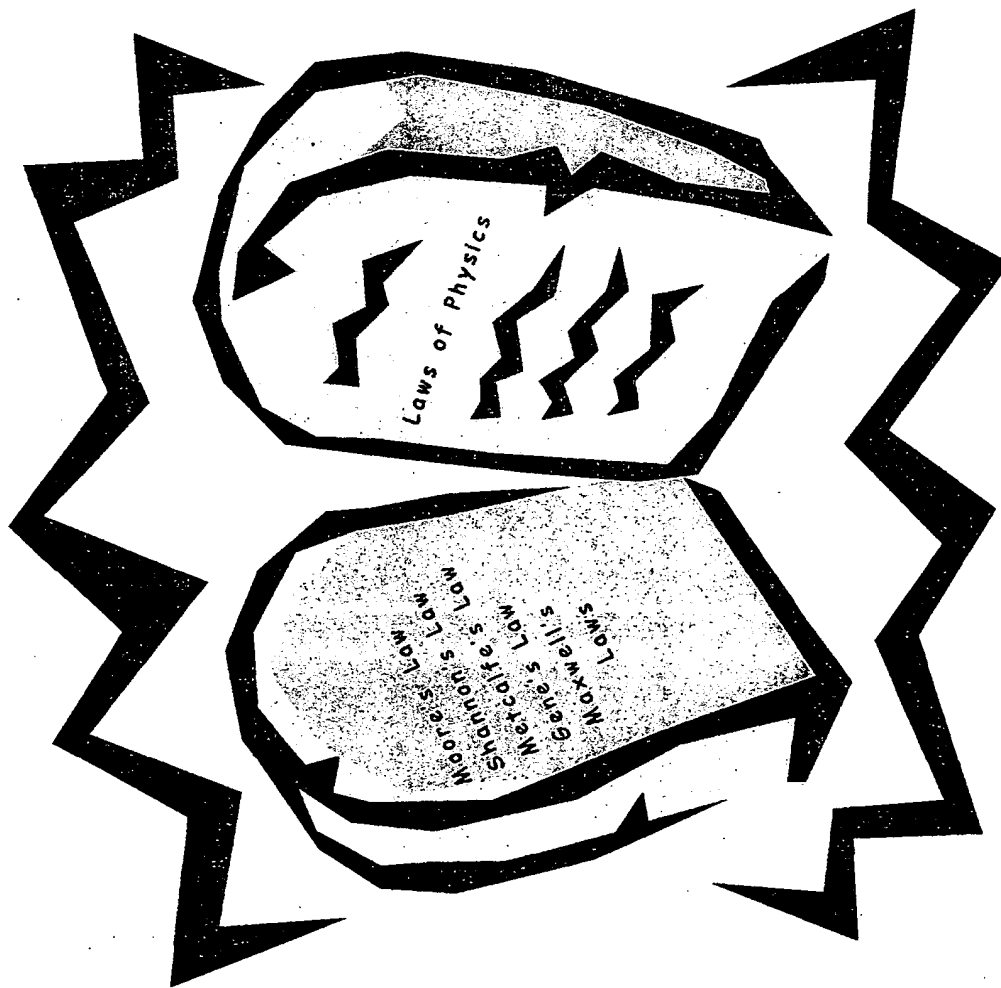
*University of California @ Berkeley*

<http://www.eecs.berkeley.edu/~jan>

**ISLPED 2001, Huntington Beach**



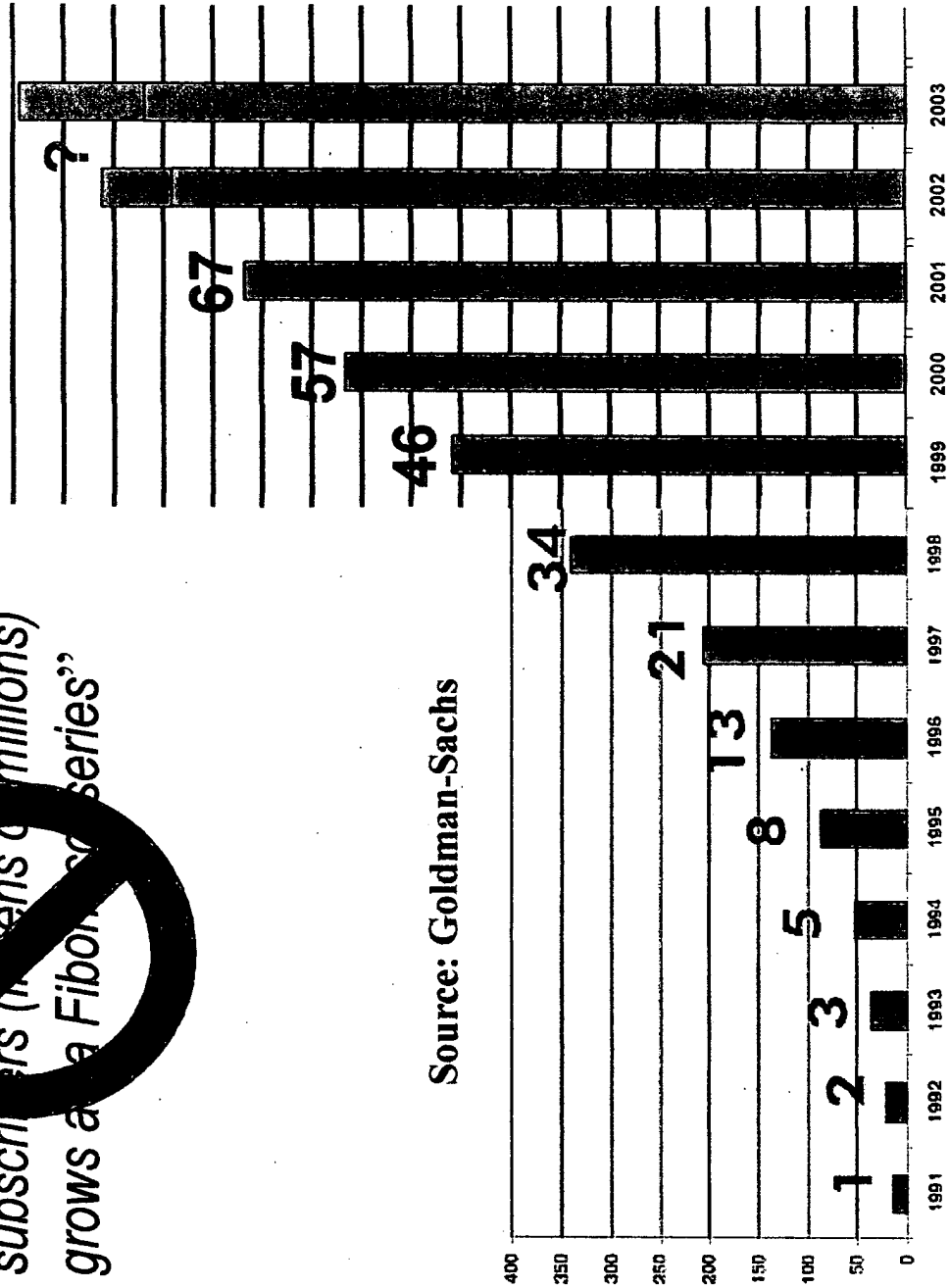
*It's all about Laws ...*



# The Fibonacci Law on Wireless Growth



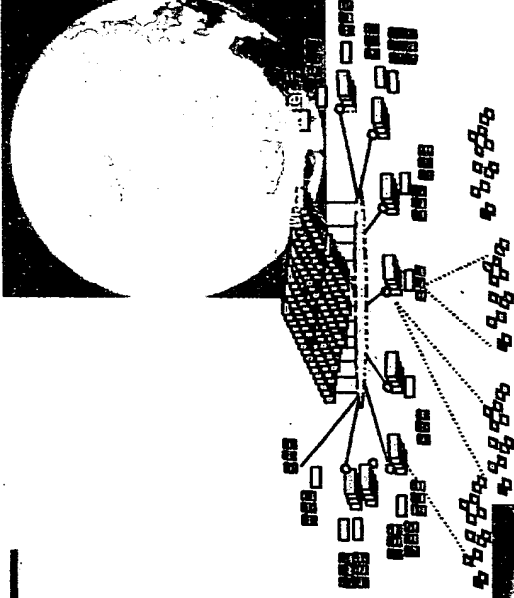
“The number of worldwide wireless subscribers (in tens of millions) grows as a Fibonacci series”



# *The Shift to Wireless Data— The New Internet*

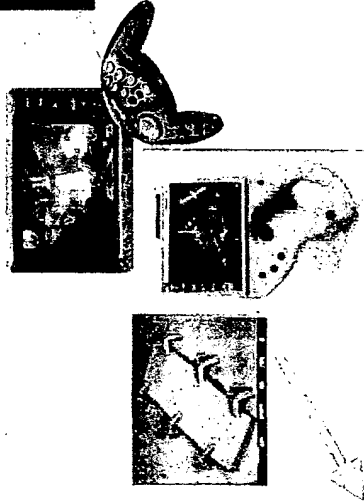
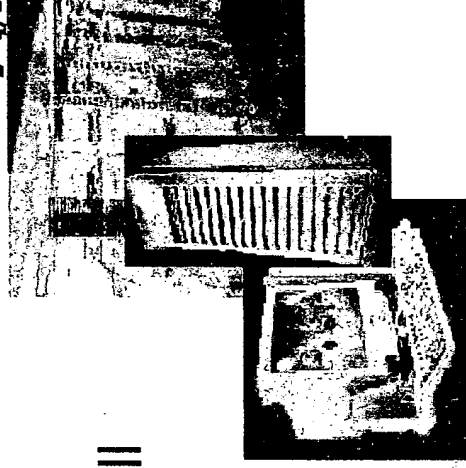
The 1990s:

Conquering the world  
The network revolution

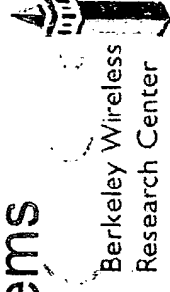


The 2000s:

Extending toward the Small  
Enabled by integration  
(Moore's Law at Work!)  
and wireless connectivity

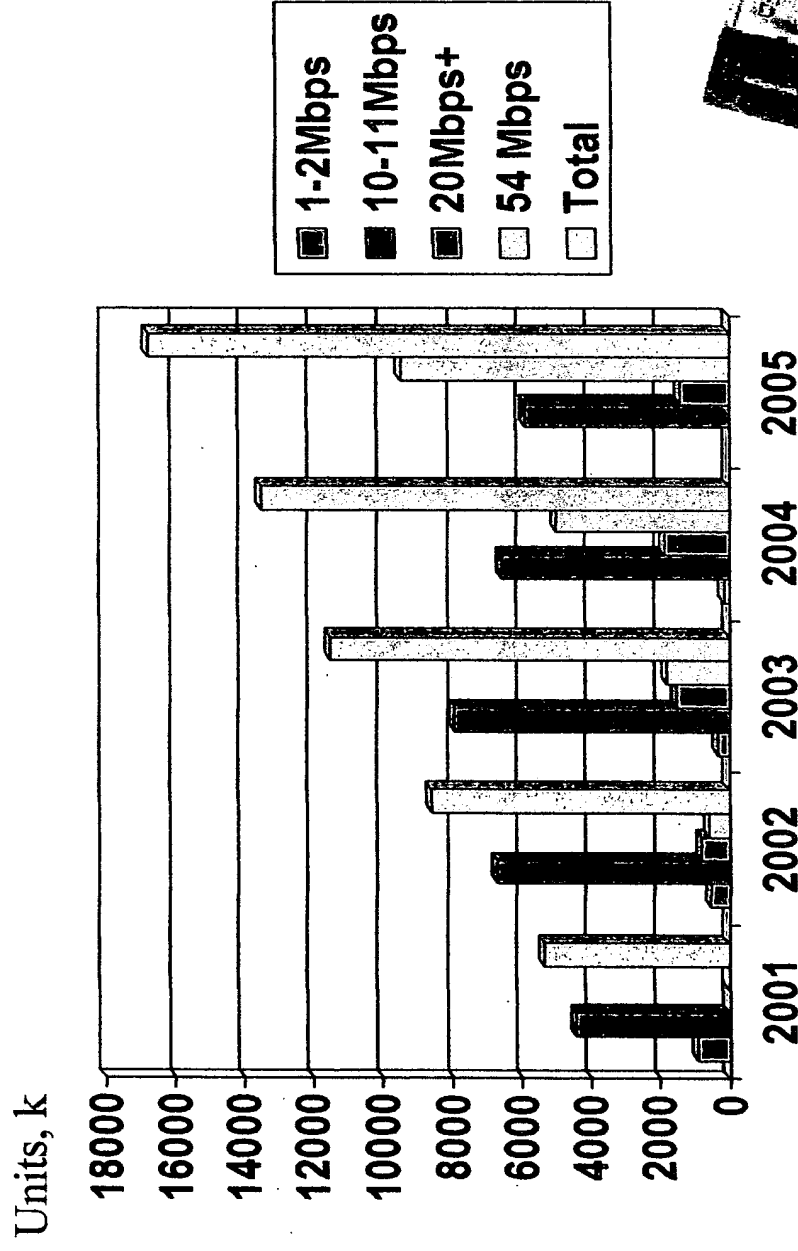


Pre-1990:  
Client-Server Systems

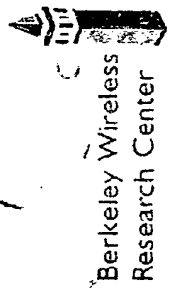


Courtesy: R. Katz, UCB

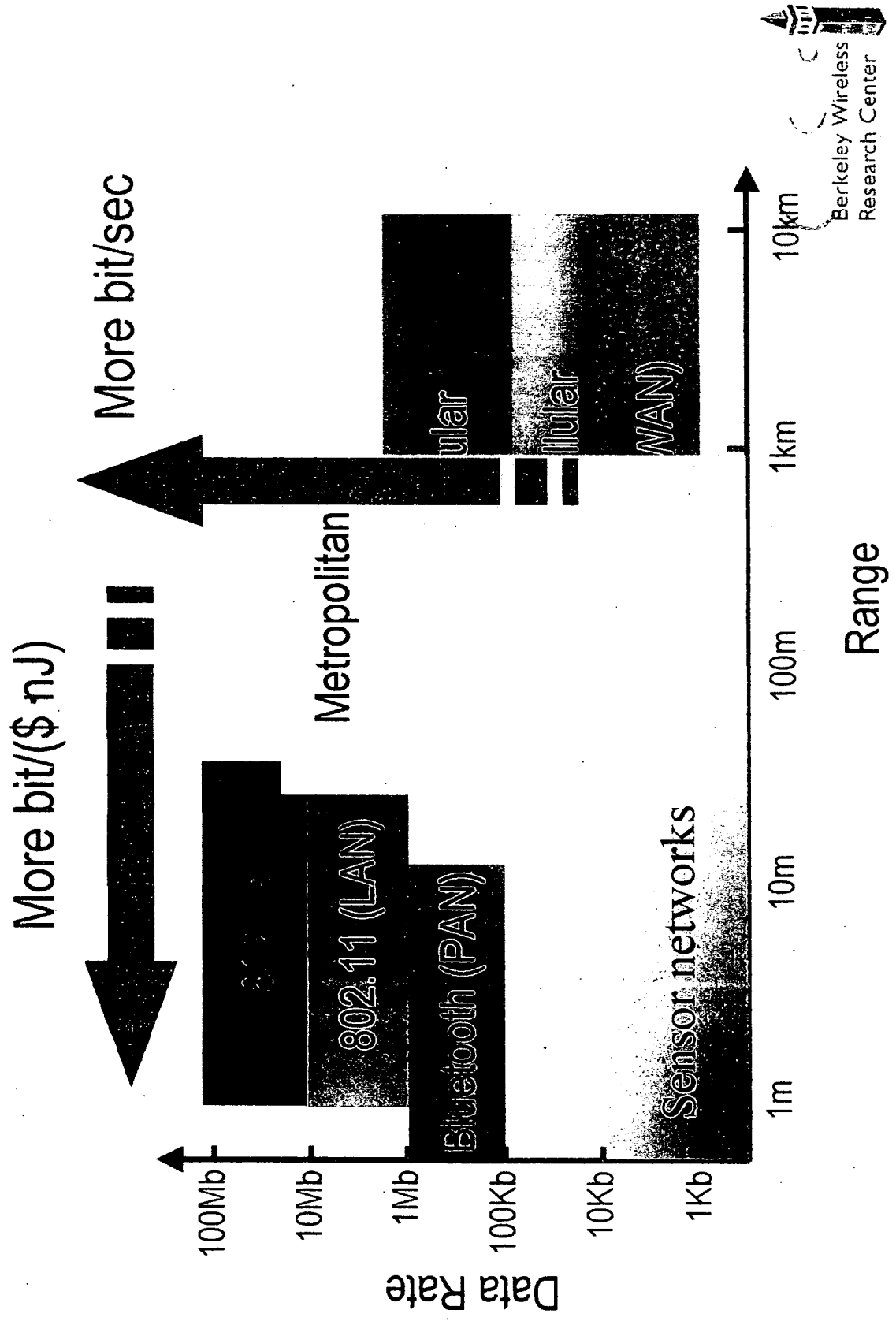
# *(Projected) Growth in 802.11 WLAN*

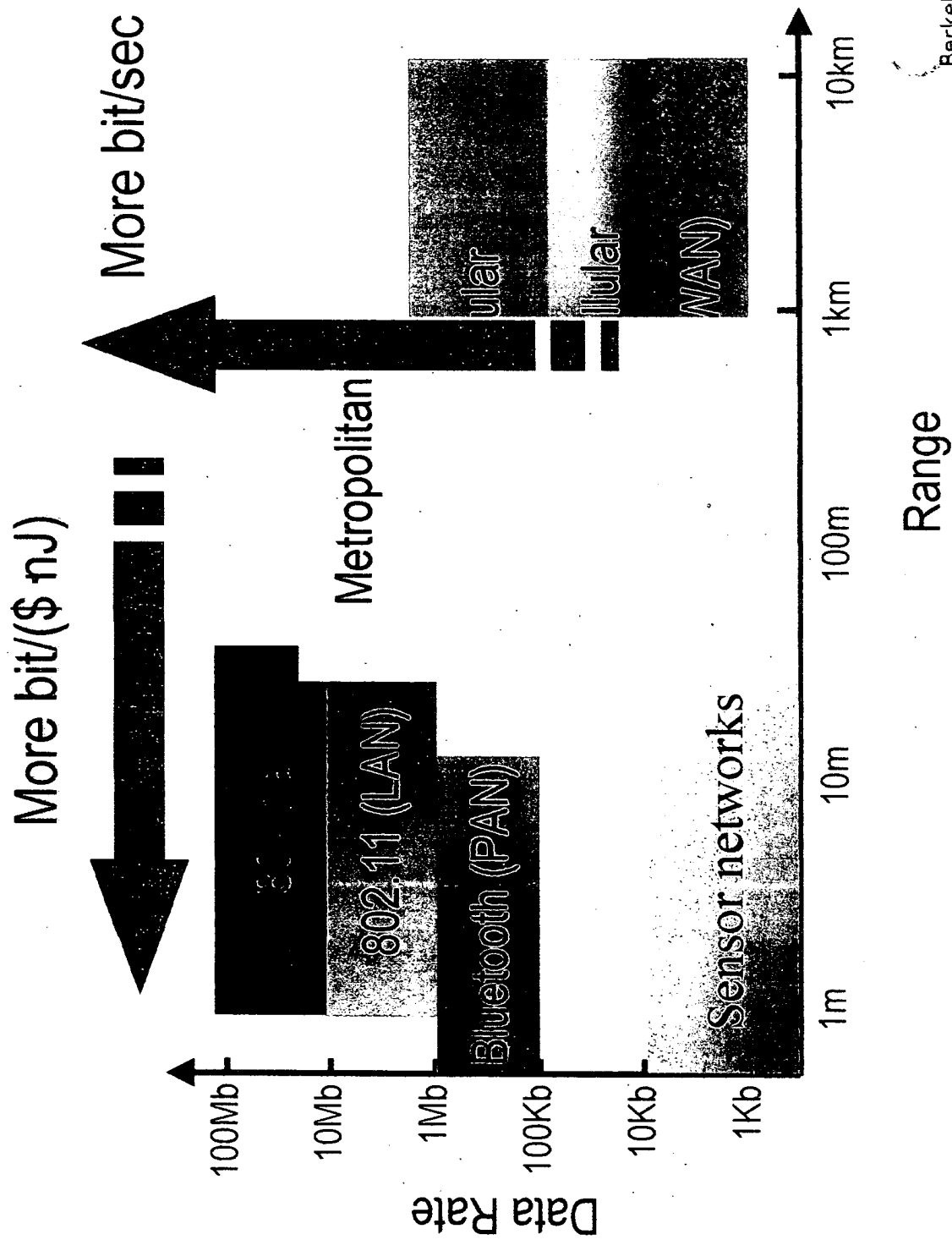


Source: Cahners In-Stat 2001



# The Evolving Wireless Scene

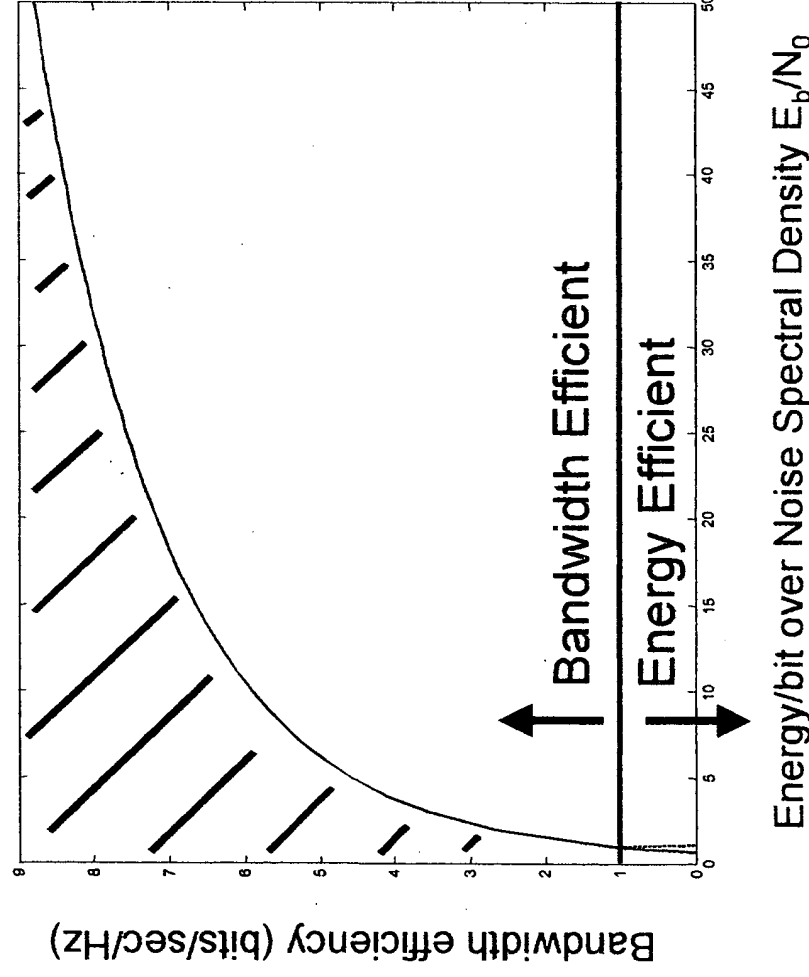




# How to Get More bits/sec in a Band-Limited Environment?

## The Shannon Bound:

In an AWGN channel, the best bandwidth-efficiency (in bits/sec/Hz) that can be achieved with arbitrarily low bit-error rate is given by

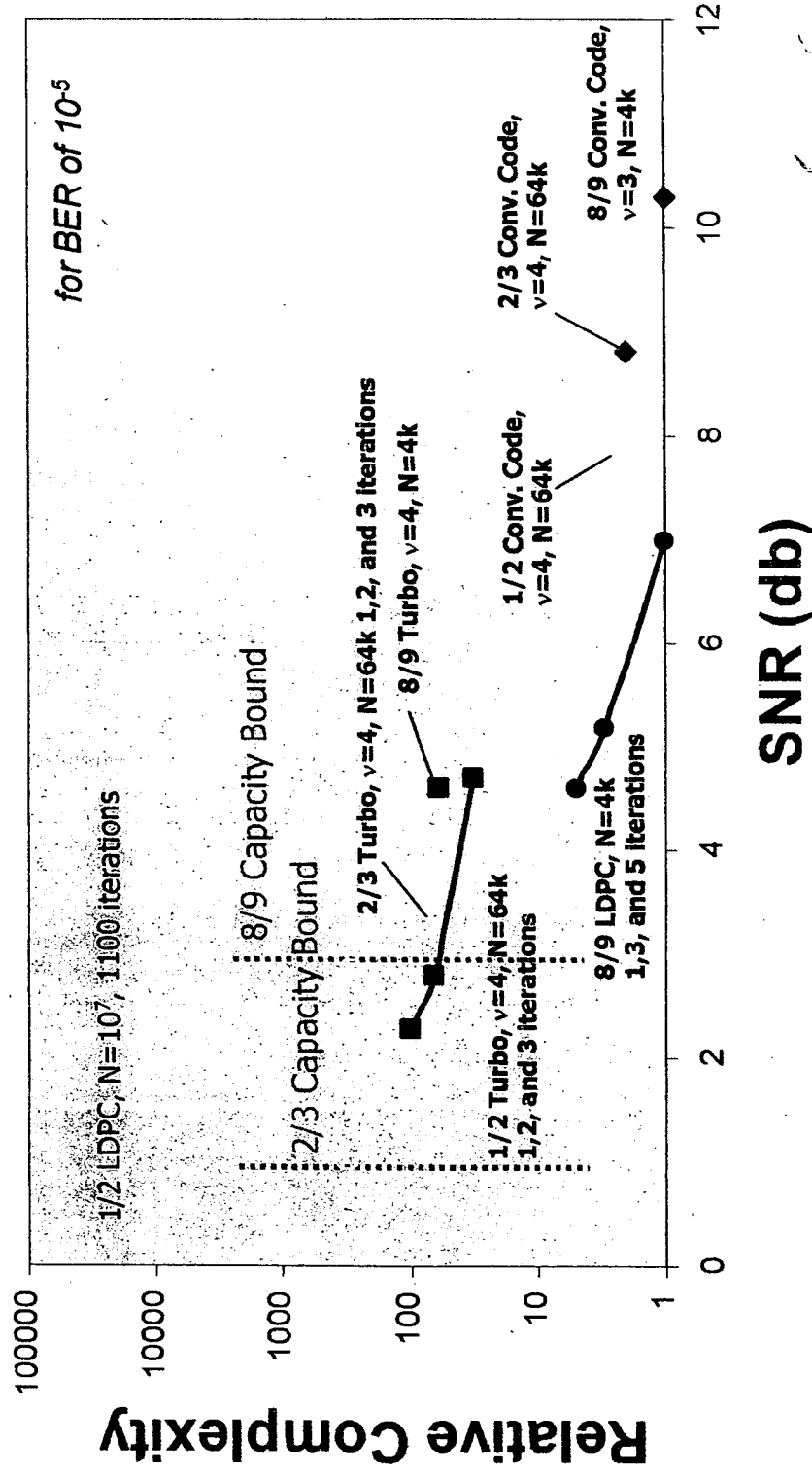


$$b_{\text{weff}} \leq \log_2 (1 + b_{\text{weff}} * E_b/N_0)$$



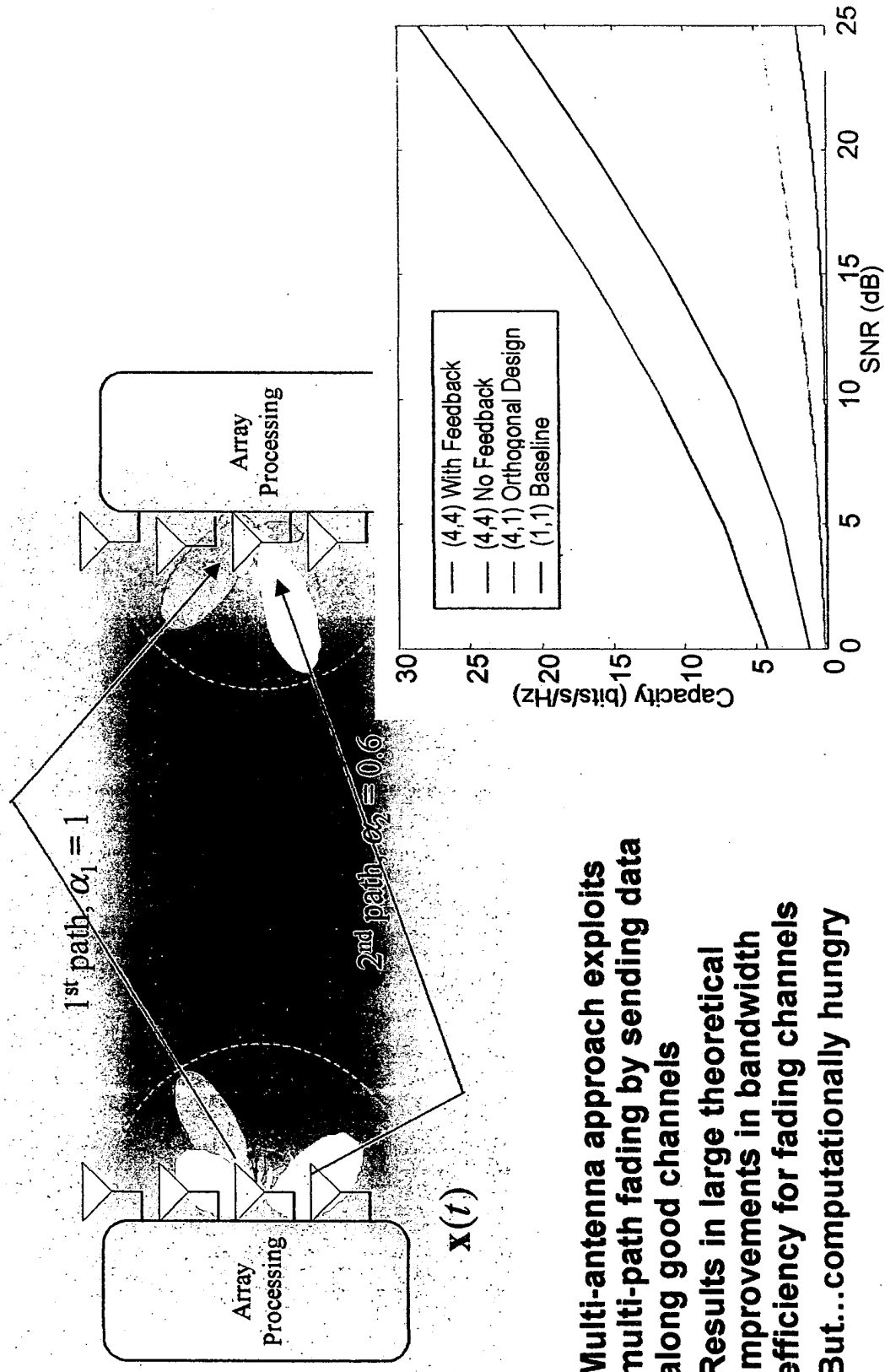
# The Cost of Approaching Shannon's Bound

## The Bliss and Challenge of Error Coding



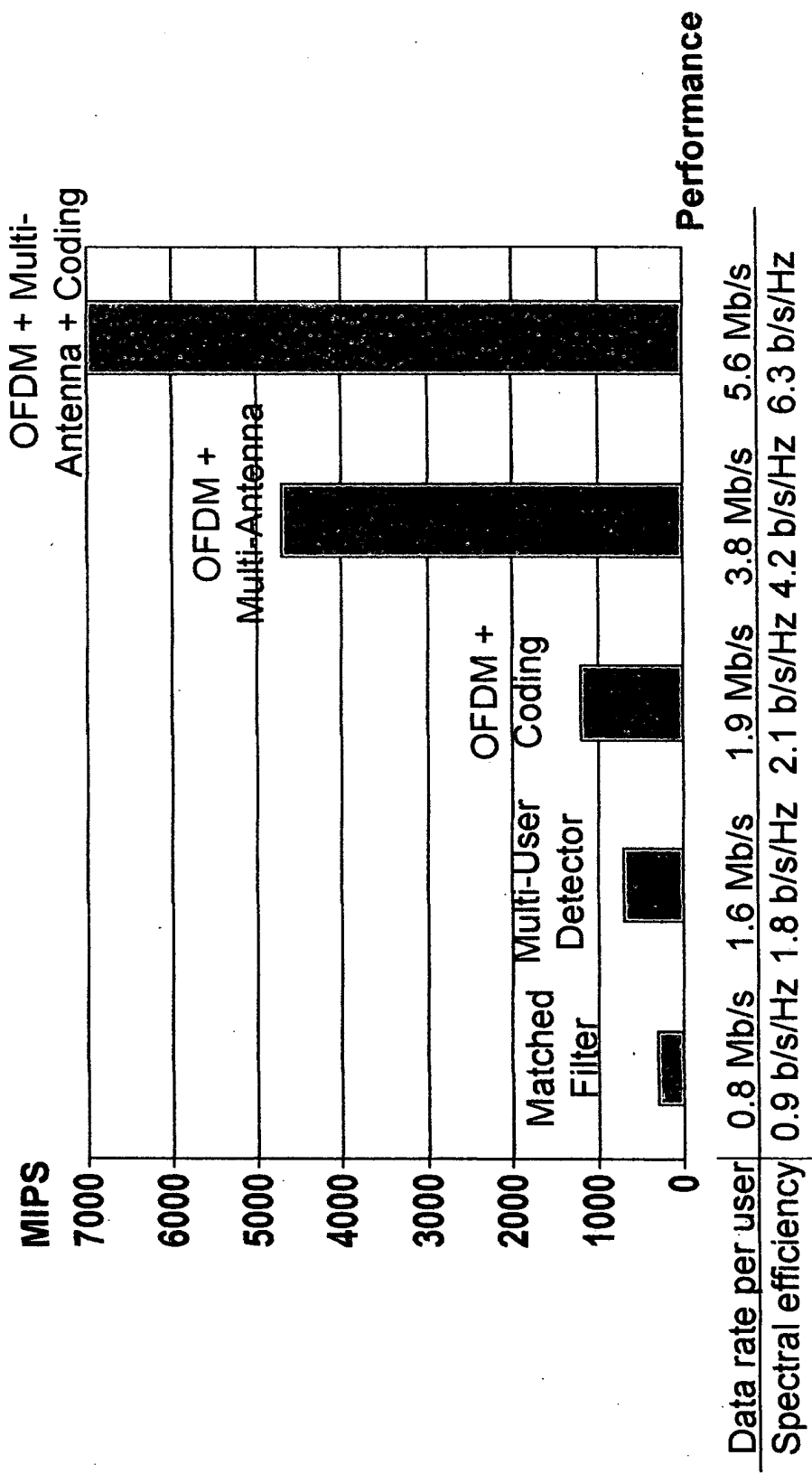
Courtesy Engling Yeo, UCB

# Dealing with Non-ideal Channels (e.g., fading)



- Multi-antenna approach exploits multi-path fading by sending data along good channels
- Results in large theoretical improvements in bandwidth efficiency for fading channels
- But...computationally hungry

# The Cost of Dealing with Non-ideal Channels



\* Assume 25 MHz bandwidth and 28 users

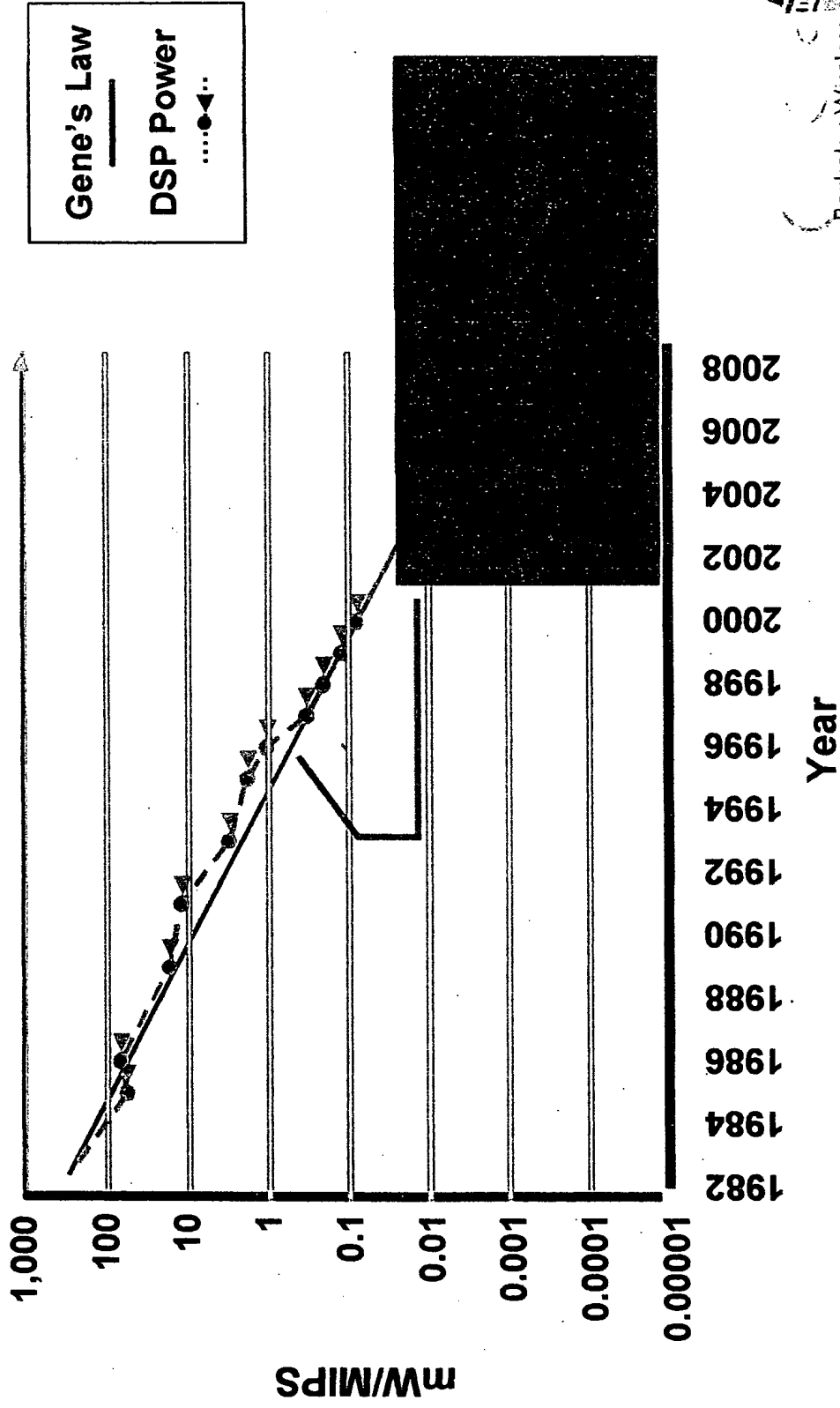
Source: Ning Zhang, UCB

# *Compelling Wireless Implementation Issues*

- **A Ferocious Quest for Performance**
  - Driven by the hunger for bits/sec
  - Outstripping the technology evolution
- **With a Premium on Reduction in Energy Consumption**
  - The compelling argument behind wireless is its untethered nature
  - Power consumption key impediment to penetration of new services
  - Energy sources on slow evolutionary path (5%/year)

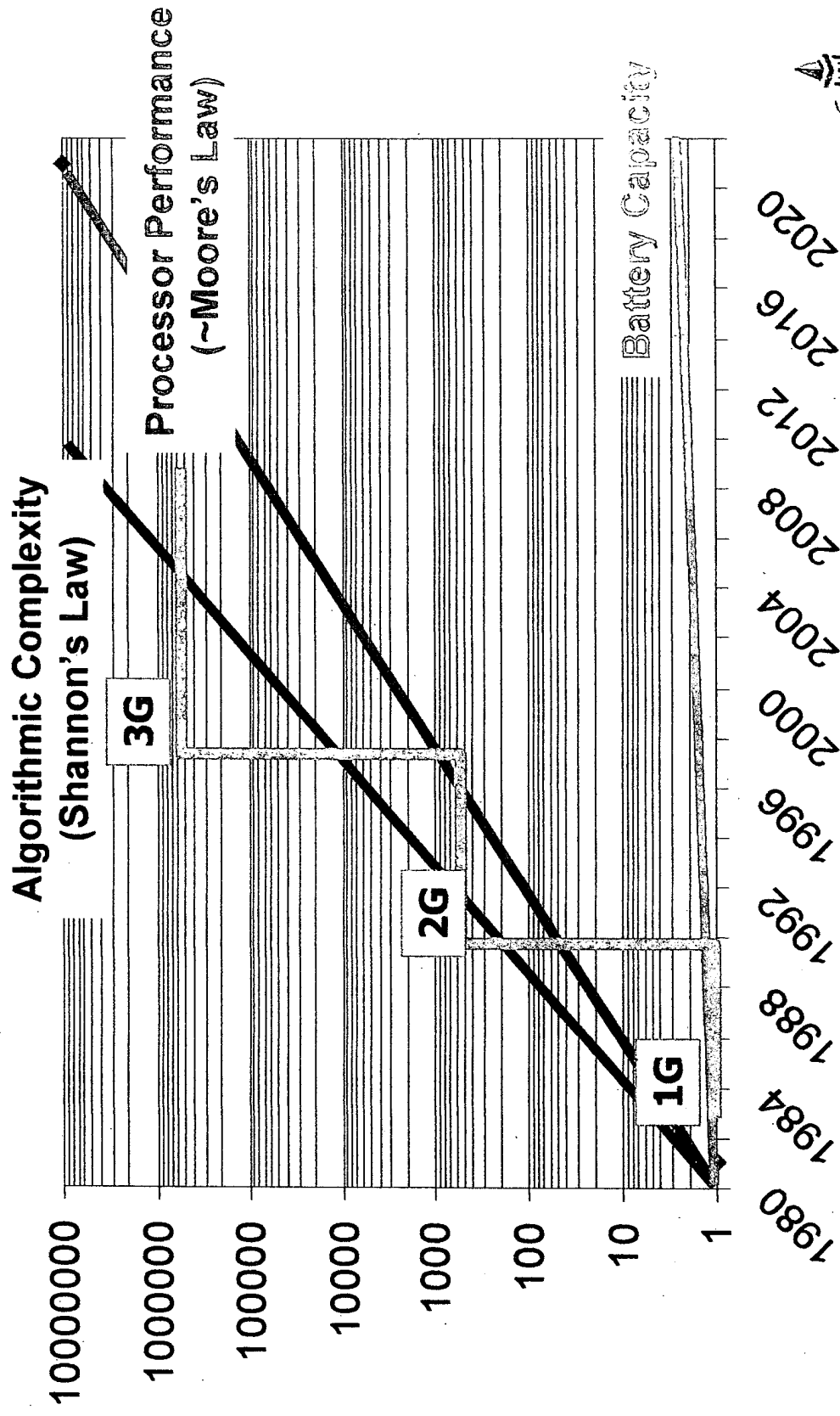
# What Technology Offers Us

## Gene (Frantz)'s Law

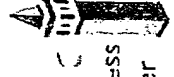


Source: Gene Frantz (TI)

# Shannon beats Moore beats Chemists



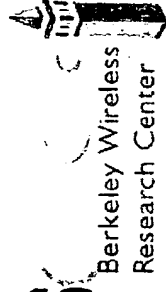
Courtesy: Ravi Subramanian (Morphics)



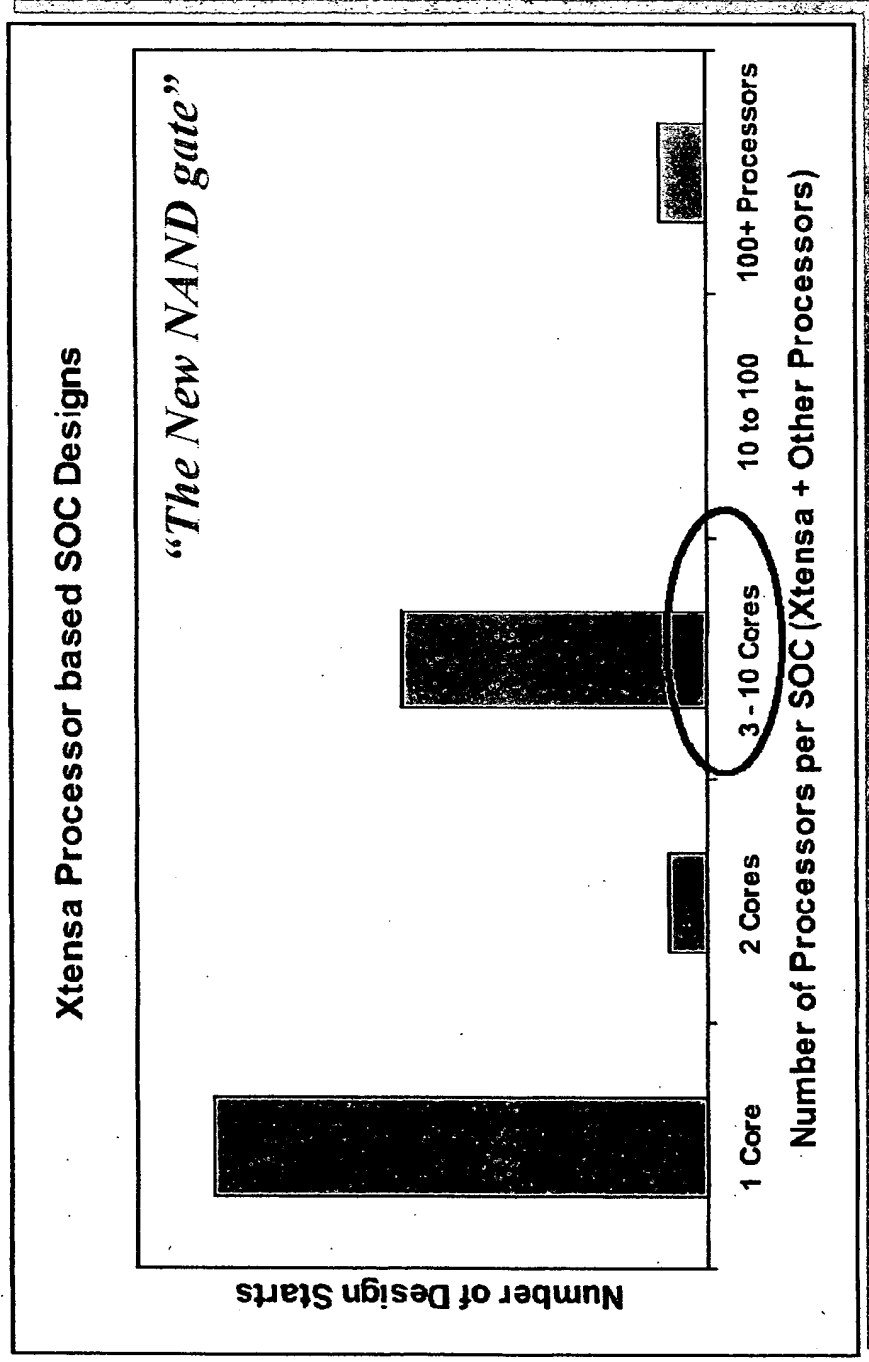
# *The Need for Flexibility*

- **Cost-of-design issues point towards component reuse**
  - Design complexity impacts time-to-market
  - Physical effects increase verification costs and design risk
  - NRE of new designs is increasing significantly (mask making, fab cost)
- **Multi-standard has become a must in the diverse wireless landscape**
- **Adaptive solutions lead to better spectral utilization**
- **A wide variety of unpredictable services**

# **Towards Fewer, but more Flexible and Reusable Silicon Platforms**

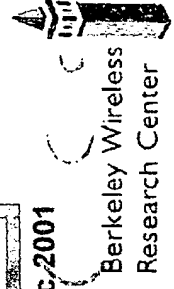


# An Attractive Option: Multi-Processor System-on-a-Chip



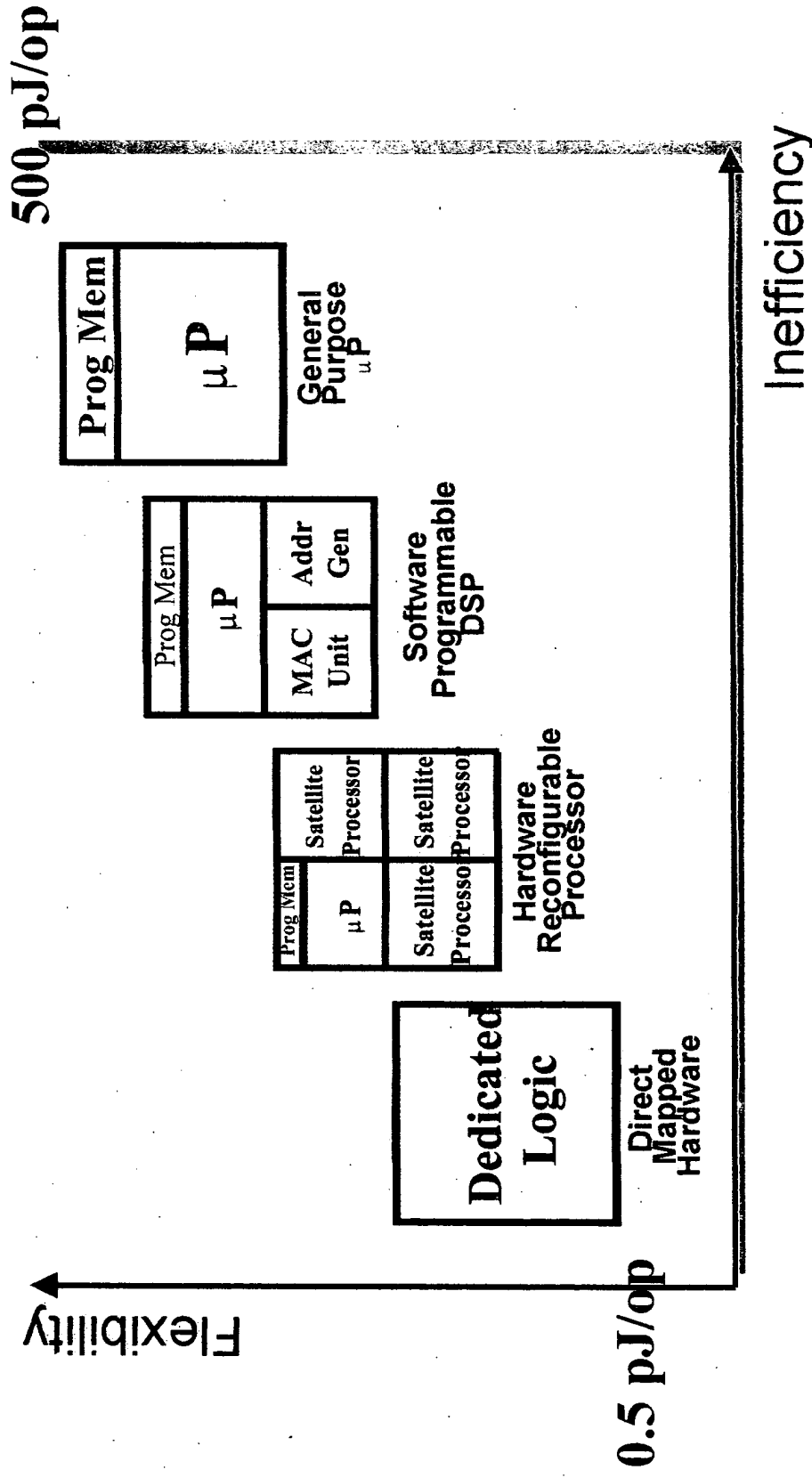
Copyright Tensilica, Inc. 2001

Courtesy: Chris Rowen, Tensilica



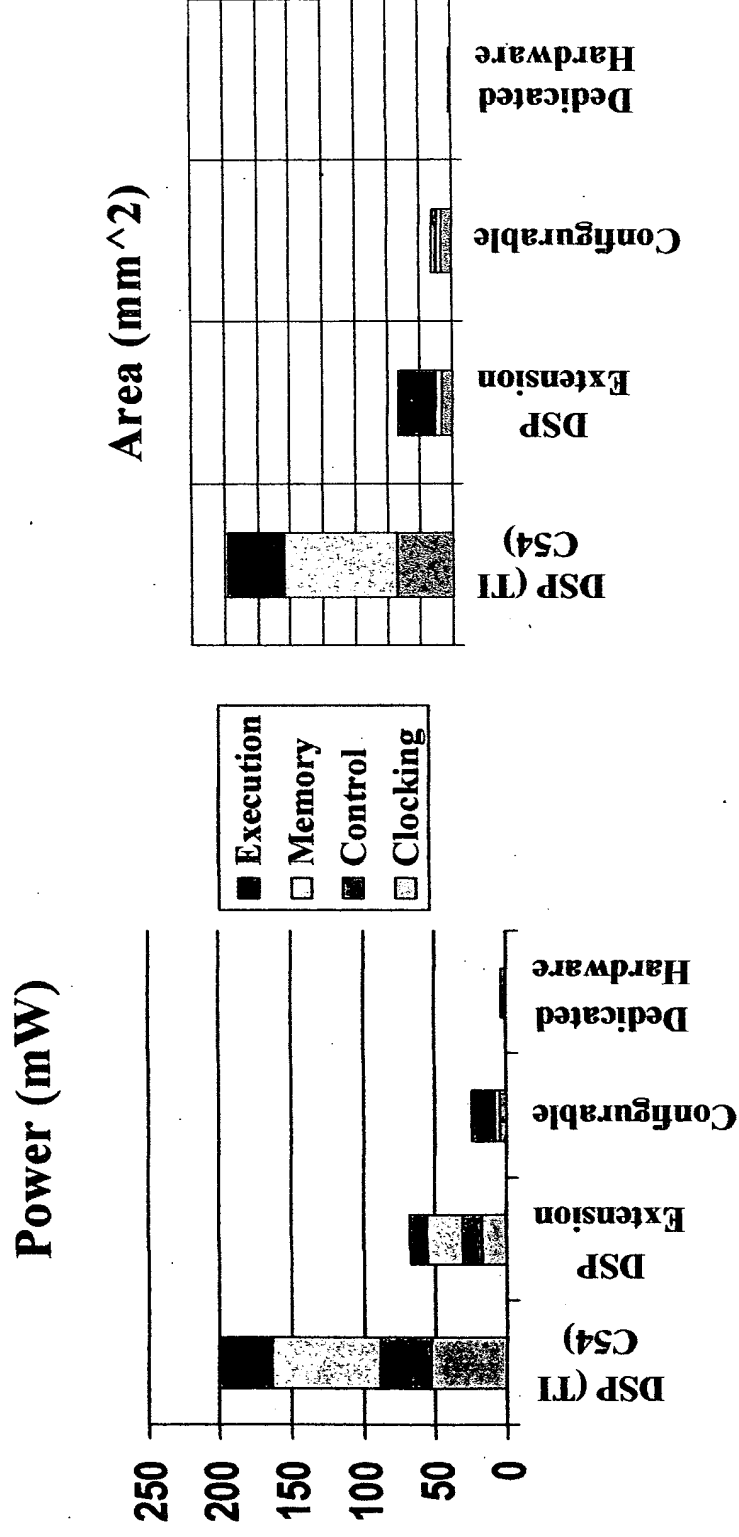


# Flexibility Comes at a Huge Cost



3 orders of magnitude!

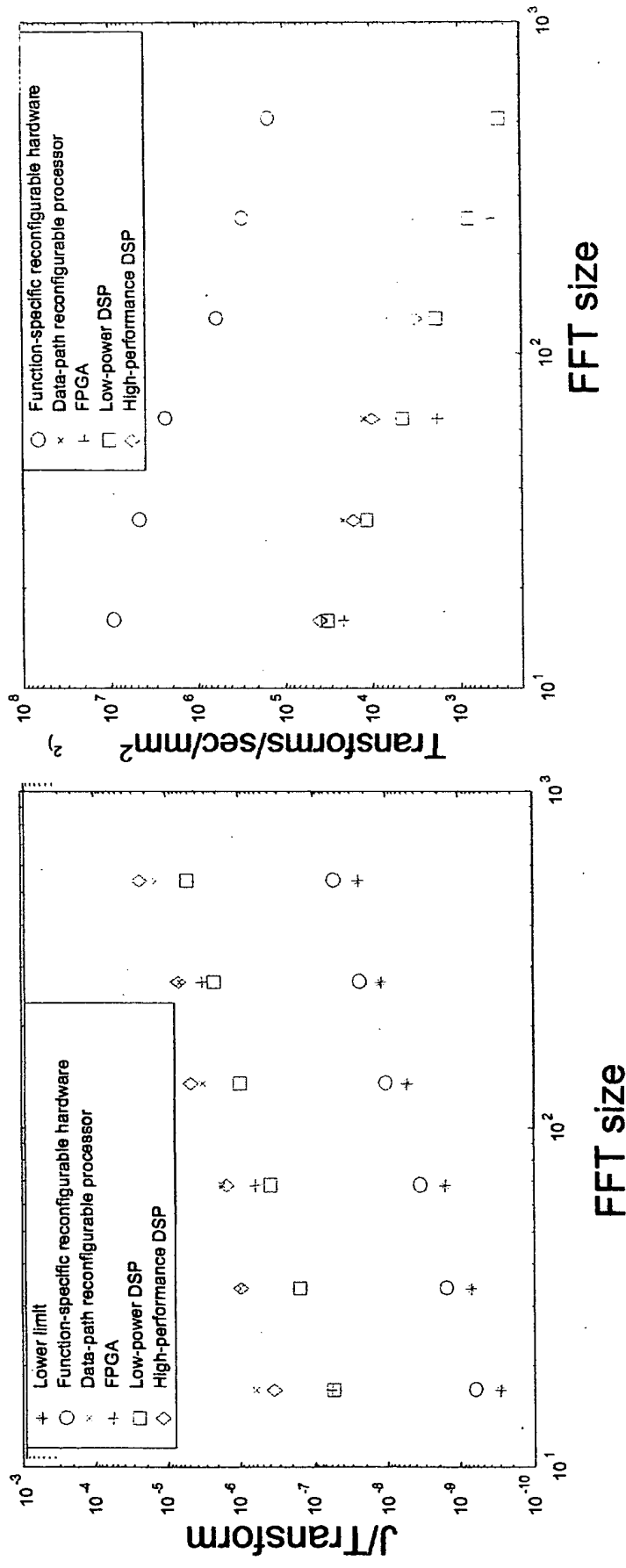
# The Opportunity of Configurable Architectures



\* Based on the implementations of a multi-user detector

Source: N. Zhang, UCB

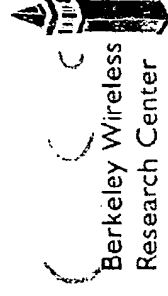
# The Opportunity of Reconfigurable— When Does it Work?



## Energy and Area Efficiency of Various FFT Implementations

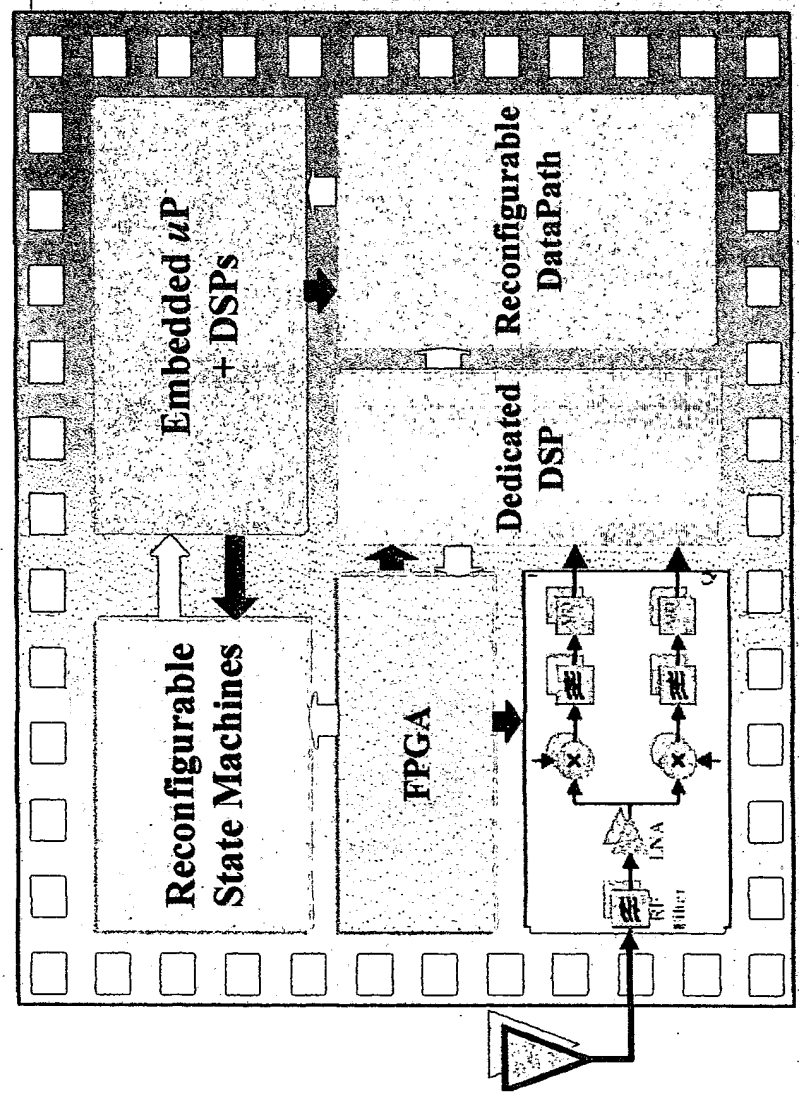
\* All results are scaled to 0.18μm

Source: N. Zhang, UCB



# The Ideal "Radio-on-a-Chip" Platform

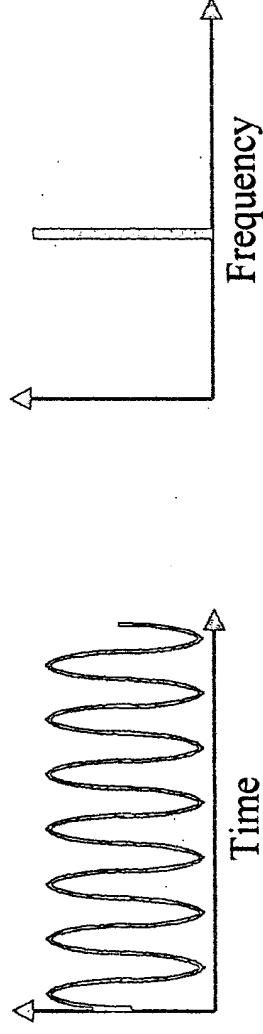
Combines performance, flexibility and energy-efficiency



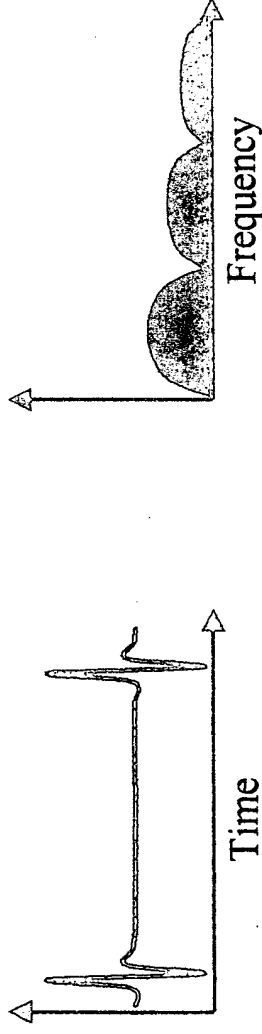
- Heterogeneous
- Matches the computational model
- Provides flexibility only where needed and desirable and at the right granularity
- Supports massive concurrency
- Operates at minimum supply voltage and clock frequency

# *An Orthogonal Approach to Bit/sec— Ultra-Wide Band Radio*

## **Traditional Sinusoidal, Narrowband**



## **Impulse, Ultra-Wideband**

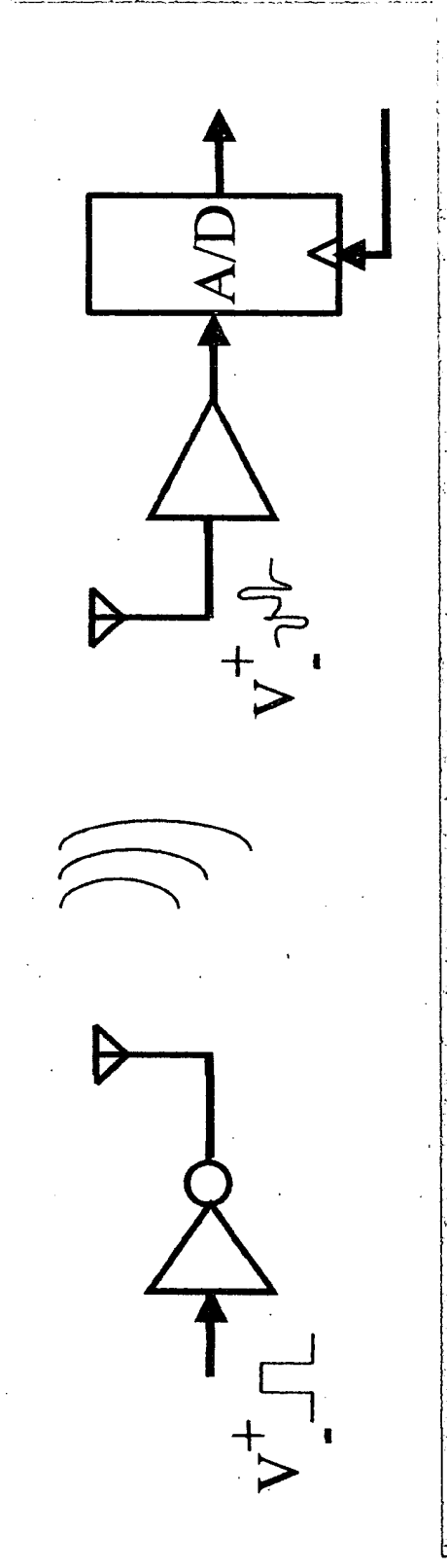


**Splurge on Bandwidth ( $> 5$  GHz) and Punt on Bit/sec/Hz**

Possible advantages: easy co-existence, low-power, simple

# Digital Pulse-Based Radio

## Simple Digital Architecture:



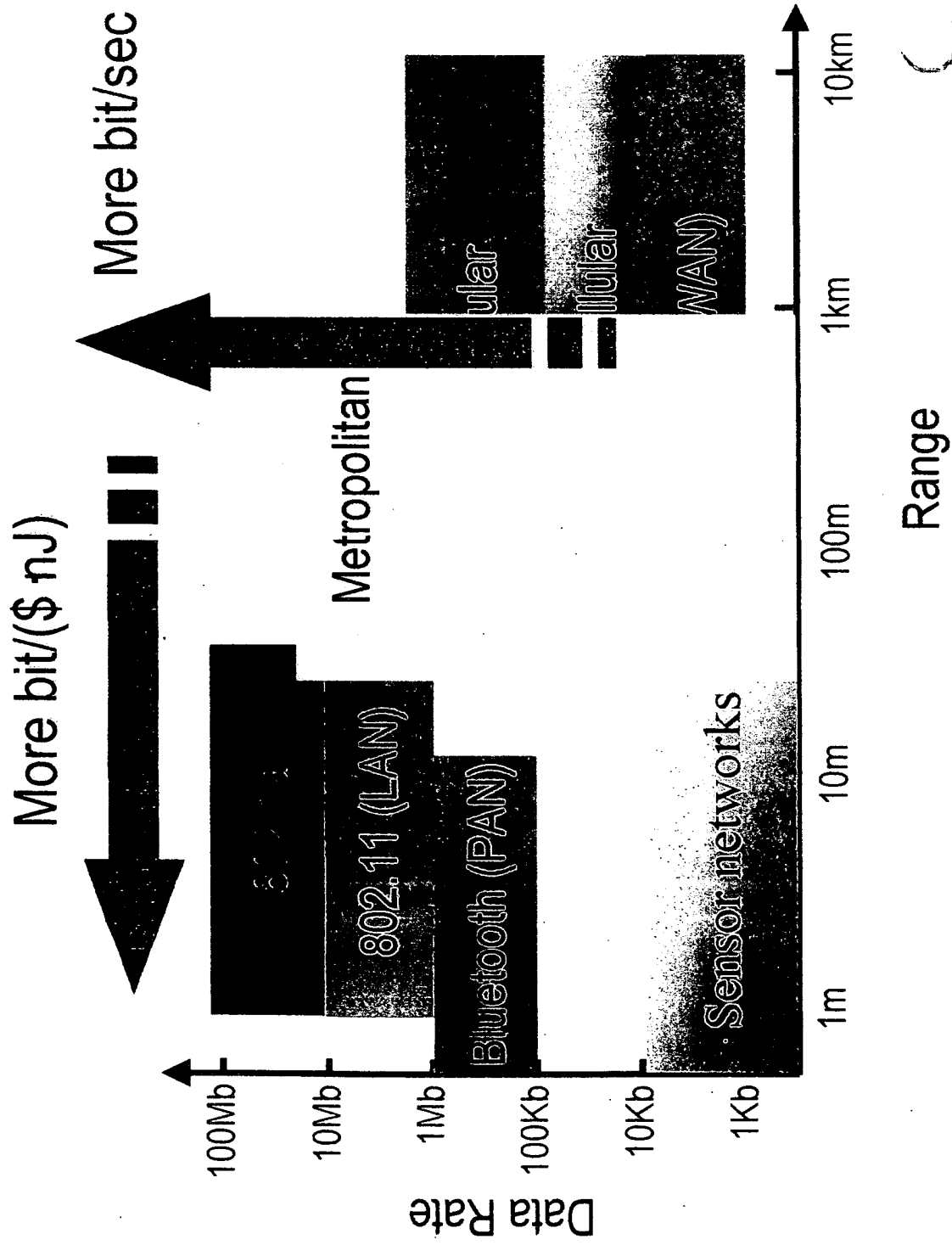
- Transmit Only Narrow Pulses (No Carrier Frequency)
- Spread Energy Over Existing Noise Floor

## The Architectural Challenge:

Providing accurate timing resolution without high-frequency clocks!

## Predicted performance:

**100 kbits/sec @  $< 10^{-4}$  bit/sec/Hz and  $\sim 10$  nJ/bit**



# *More Bits/(nJ·\$·mm<sup>3</sup>): Wireless Sensor Networks*

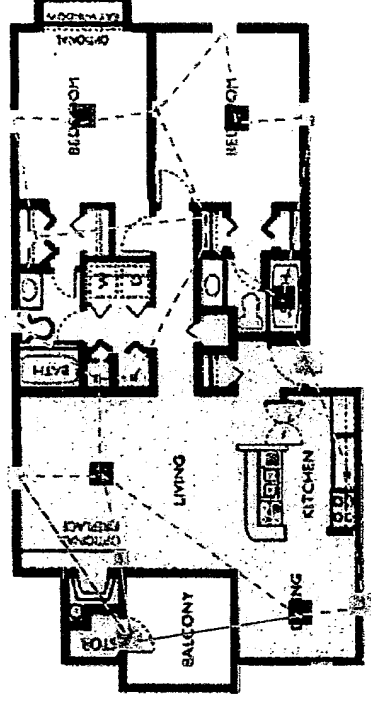
Pushing the Bounds in Ultra [Small, Cheap, Low-Power]

## **Berkeley PicoRadio's**

Meso-scale low-cost radio's for ubiquitous wireless data acquisition in sensor/actuator networks that are fully integrated and consume less than 100  $\mu$ W enabling energy scavenging

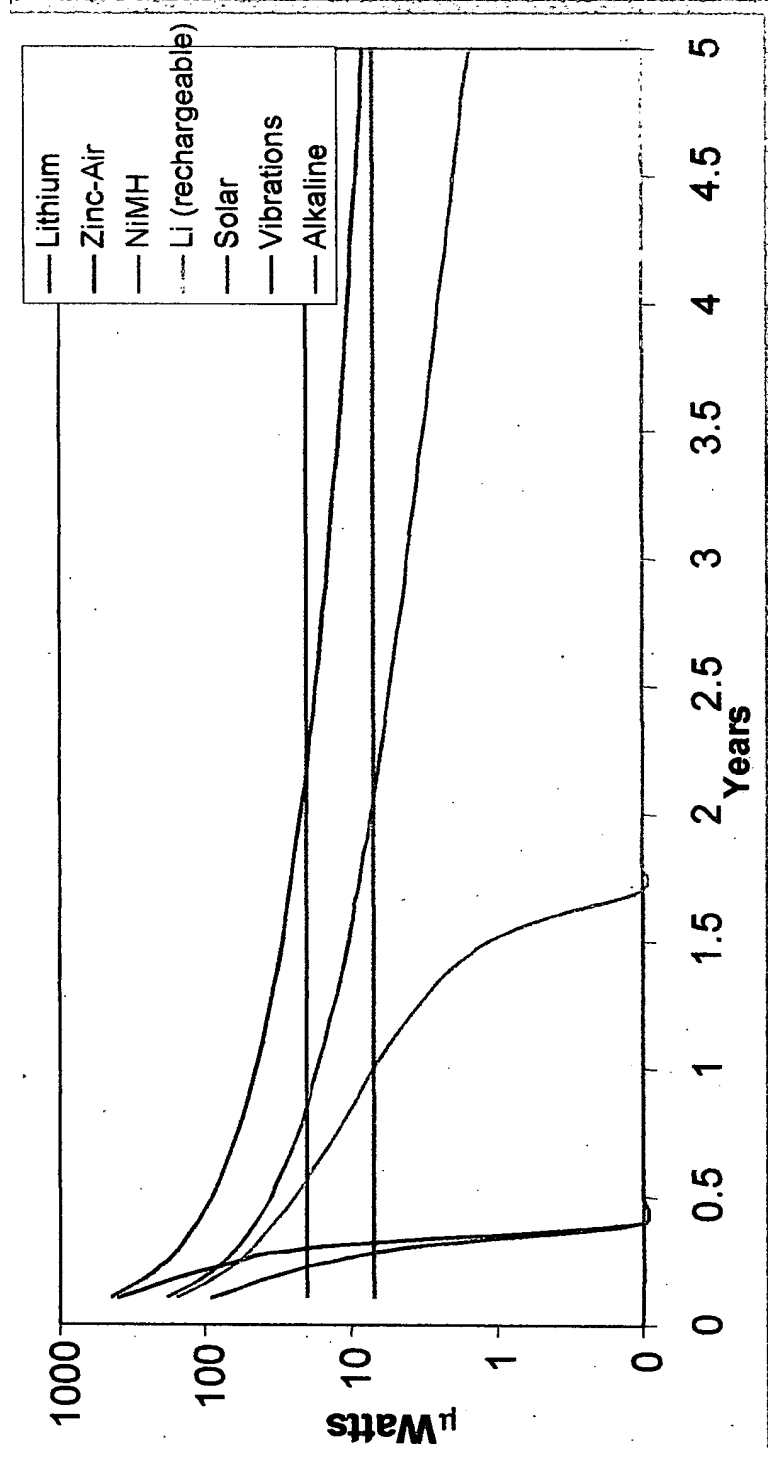
## **The Smart Building Integrated Sensor/Actuator/ Control System**

- Improves quality-of-living
- Saves energy
- Provides security
- Helps localizing items
- Extends building-human interface





# The Energy-Scavenging Opportunity



**Battery size: 0.5 cm<sup>3</sup>**

**Vibration: 1 cm<sup>2</sup> piezo-electric**

**Solar: 1 cm<sup>2</sup> single-crystal**

**Courtesy: S. Roundy (UCB)**

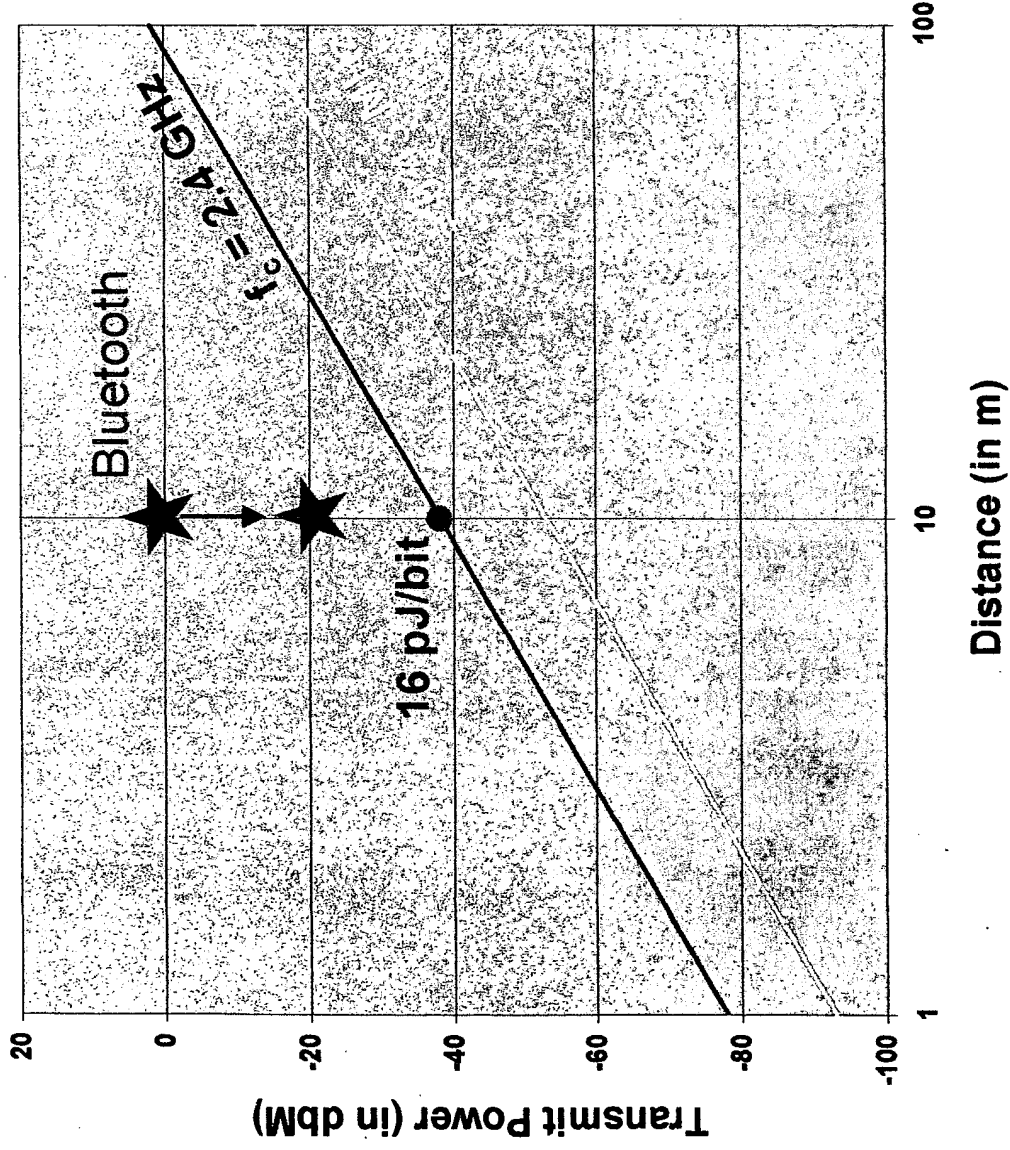
# Opportunity: Metcalfe's Law

*"The true value of a network increases as the square of the number of users on the network"*

## A Variant: Jan's Law

*"The power efficiency of a wireless sensor node increases as the square of the number of nodes in the network (or is proportional to the node density)."*

# Addressing the Communication Cost

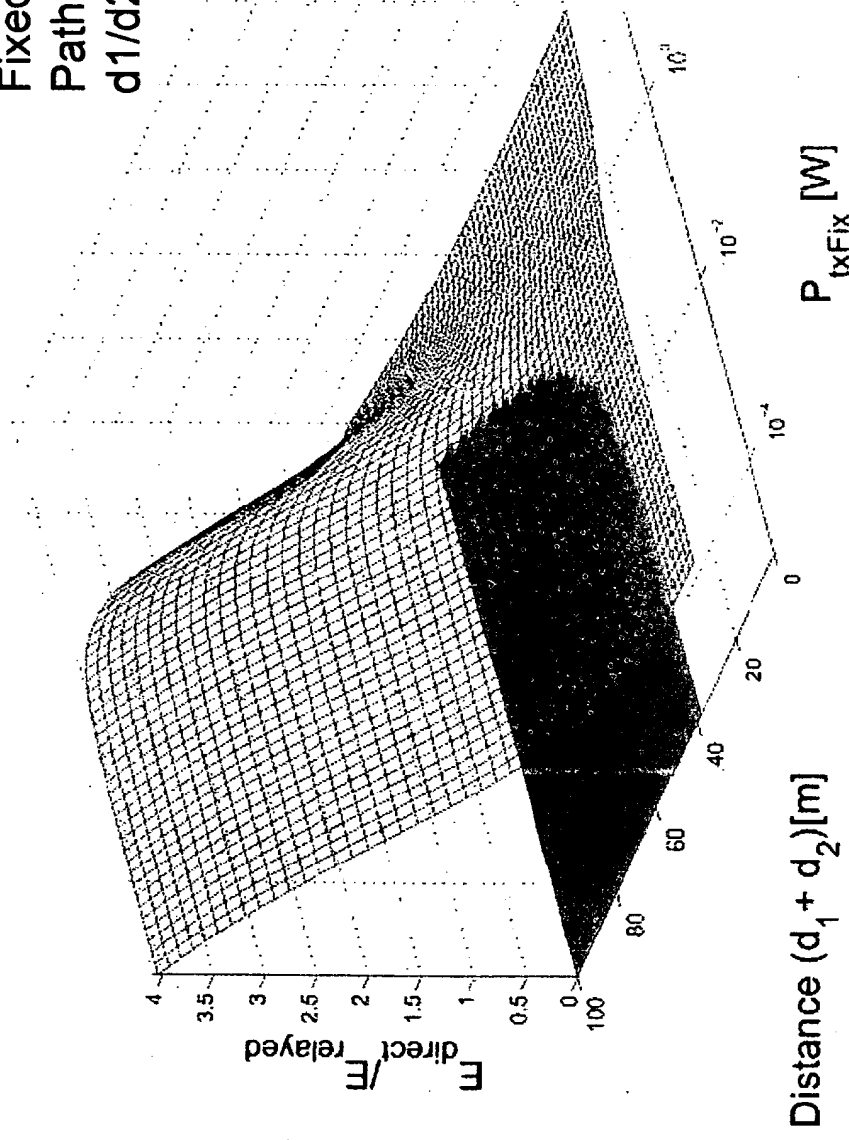


(assuming  $d^4$  path loss of and 10 kB/sec data rate)

- Minimum required transmit power increases as  $d^4$  due to ground wave and multi-path
- Increasing carrier frequency costs 20db/decade

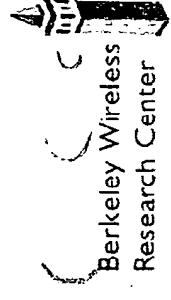
# Adding a Single Relay Point in a Wireless LAN

Bit-rate: 6 Mb/sec  
Packet Error Rate: 1%  
Fixed Receiver Power: 100 mW  
Path Loss Exp.: 3.8  
 $d_1/d_2 = 1$

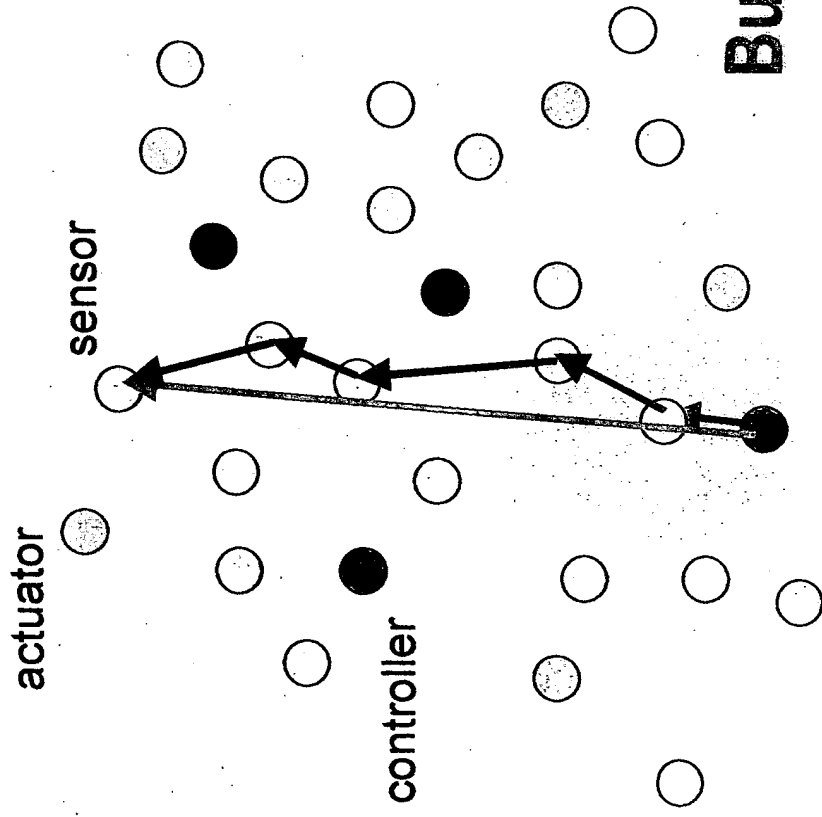


**Reduces energy/bit  
up to 4 times!**

Source: M. Kubisch and H. Karl, TU Berlin



# Trading-off Latency for Energy: Self-configuring Multi-hop Networks

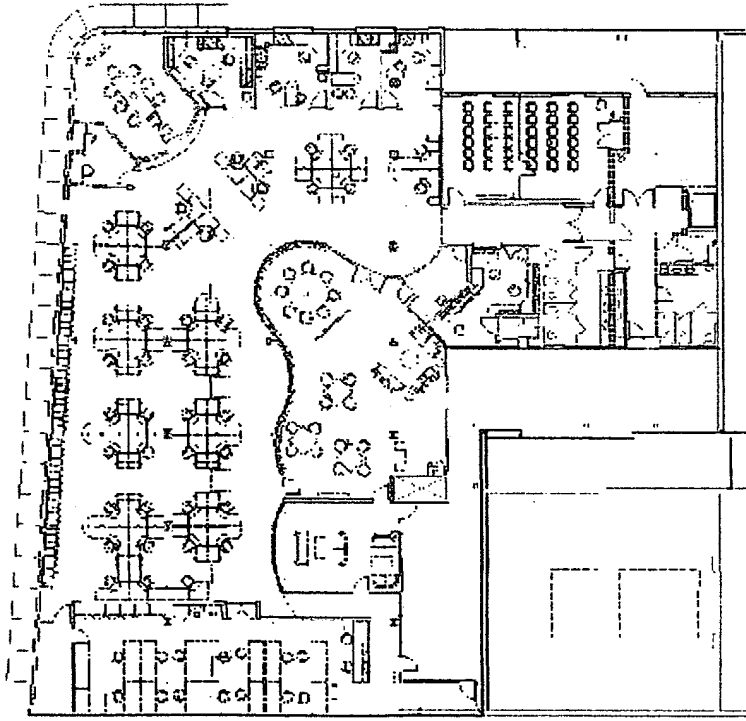


- 1 hop over 50 m  
1.25 nJ/bit
- 5 hops of 10 m each  
 $5 \times 2 \text{ pJ/bit} = 10 \text{ pJ/bit}$
- Multi-hop reduces transmission energy by 125!

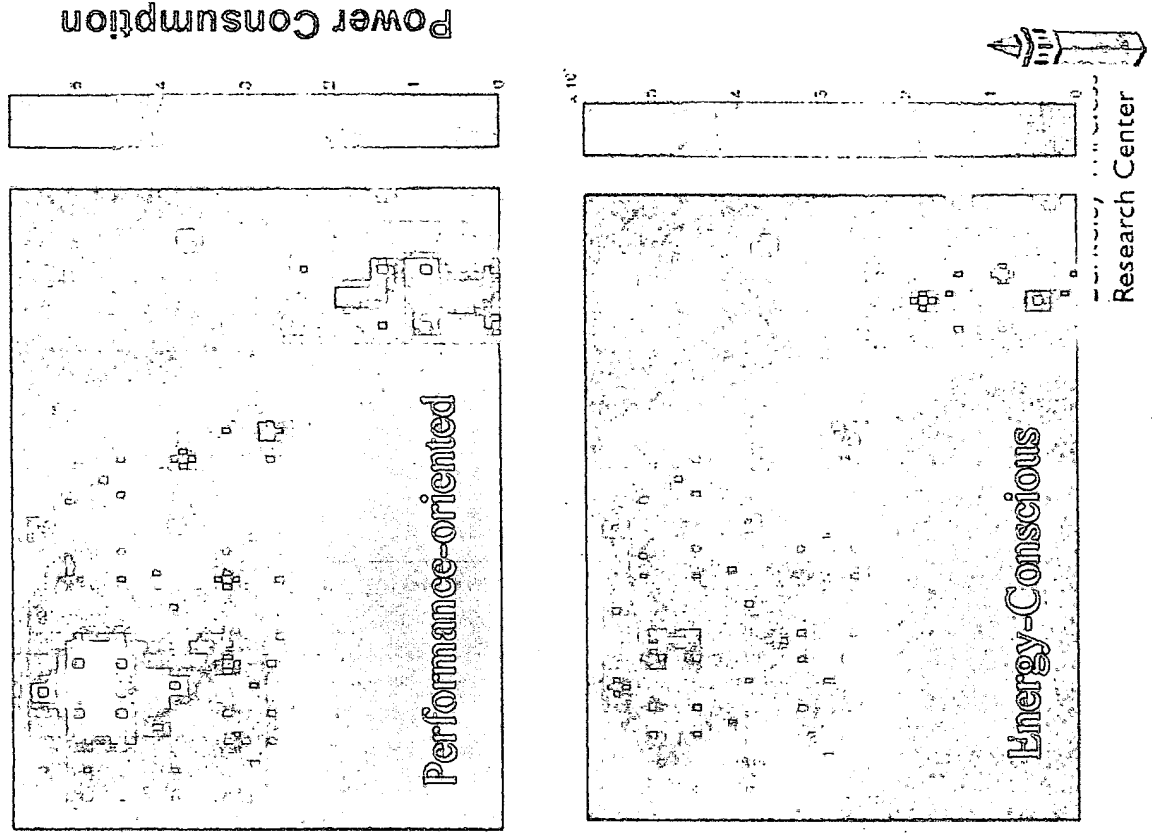
**But ...how to ensure fairness?**

# Energy-Conscious Networking

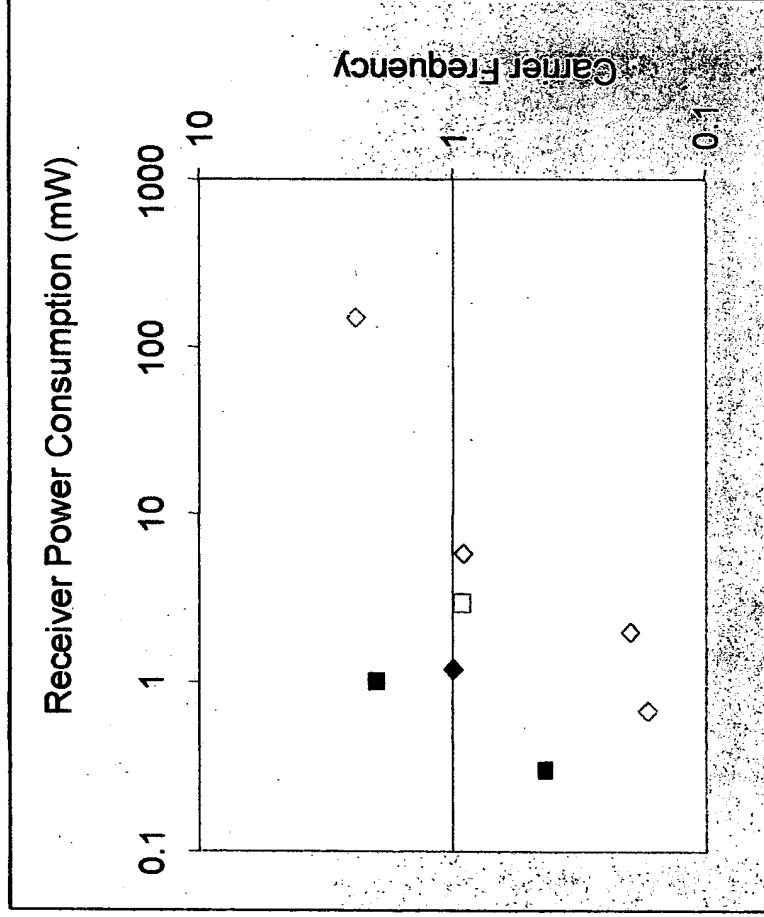
Simulated Energy Dissipation  
in Sensor Networks (BWRC)



Source: R. Shah (UCB)



# The Sensor-Node RF Challenge

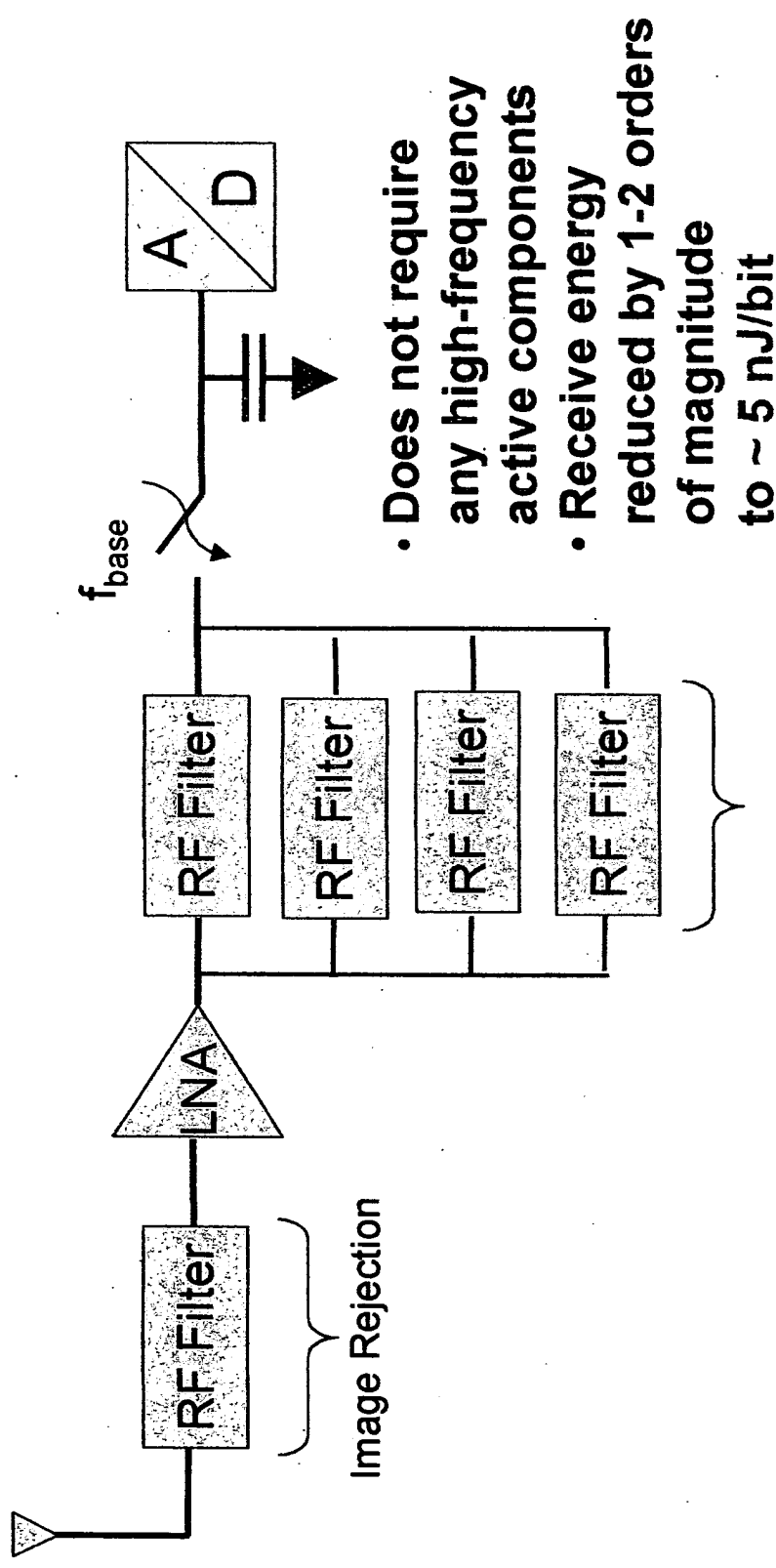


- **Increasing carrier frequency increases power dissipation**
  - Mostly due to higher speed active components (synthesizers, mixers, A/Ds)
- **But enables higher integration**
  - Smaller sizes of passives and antennas

**Rx power consumption versus carrier frequency for a number of low-data rate, small-distance RF implementations (all operate in Shannon's "energy-efficient zone")**

# Eliminating most High-Speed Components

## Sub-sampling receiver with passive frontend



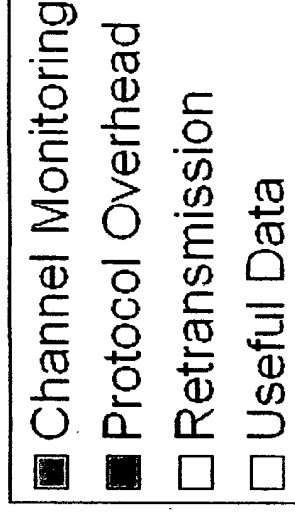
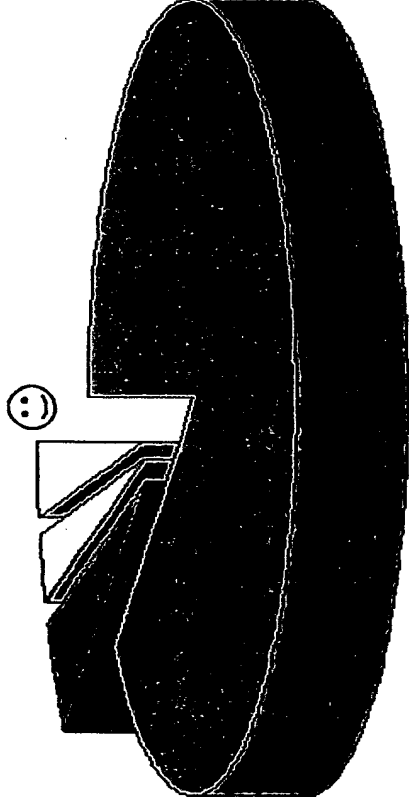
Provides diversity  
Shapes LNA thermal noise





# *The Importance of Power Management*

- Activity in sensor (data) networks is low and random ( $< 1\%$ )
- Receiving a bit is computationally more expensive than transmitting one
- Most Media Access protocols assume that the receiver is always on and listening!

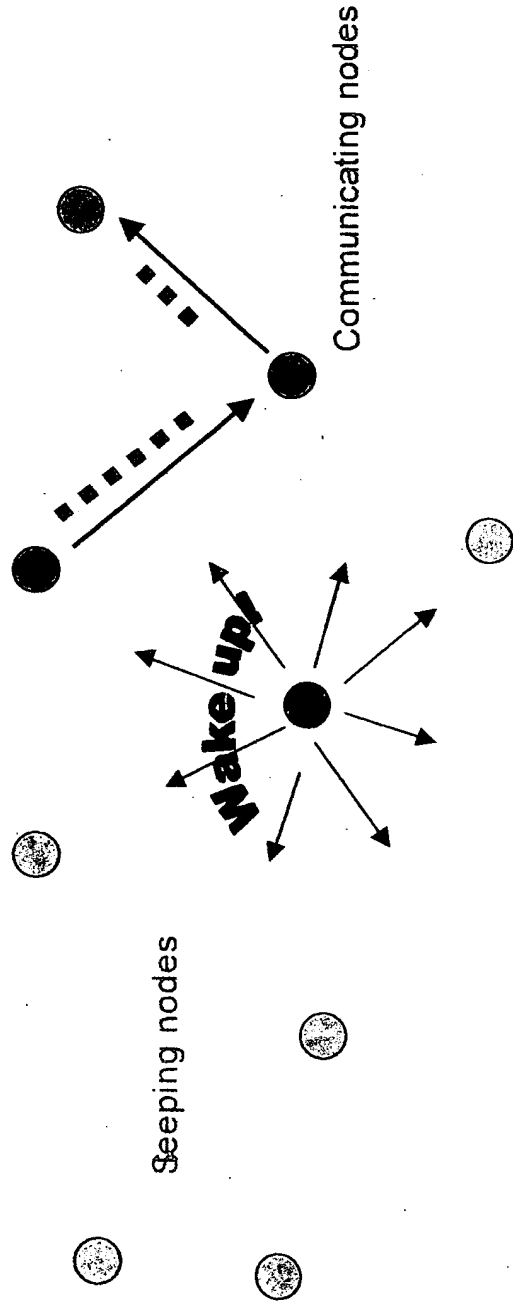


**Why not power transceiver up for real events only  
(incoming data, sensor event, network maintenance)?**

# Reactive Media-Access Control

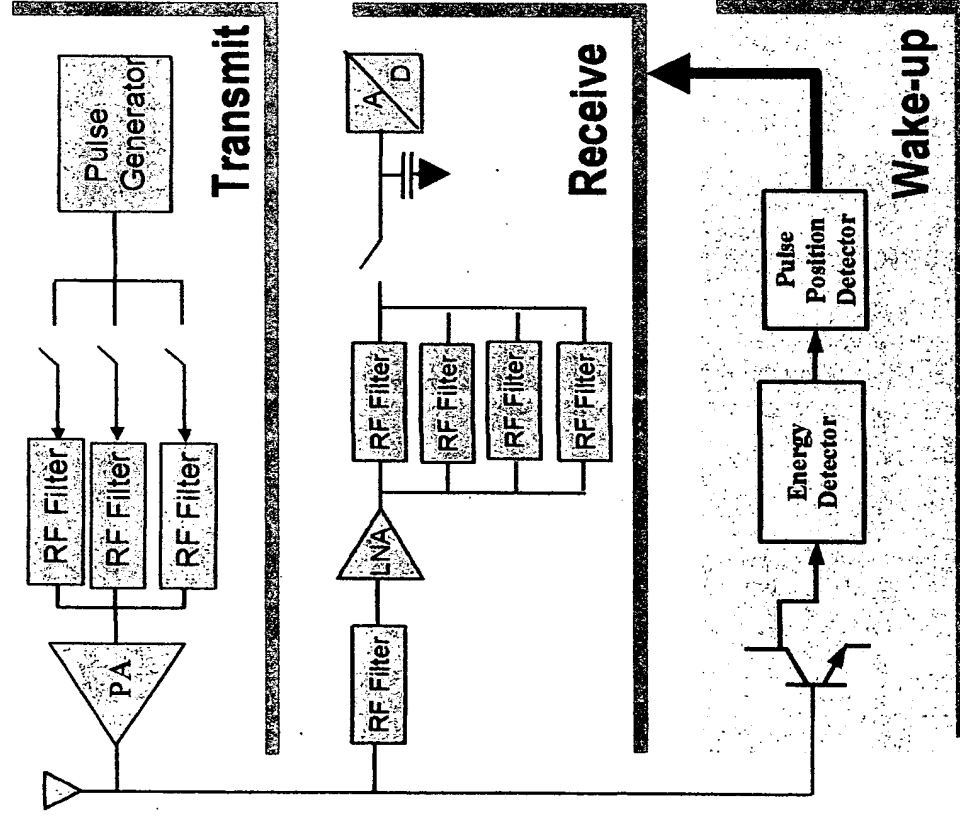
## Truly Reactive Messaging at the Physical and Media-Access Level

- ❖ Power Down the Whole Data Radio
- ❖ Reduces Monitoring Energy Consumption by  $10^3$  Times
- ❖ Wakeup Radio Powers Up Data Radio for Data Reception

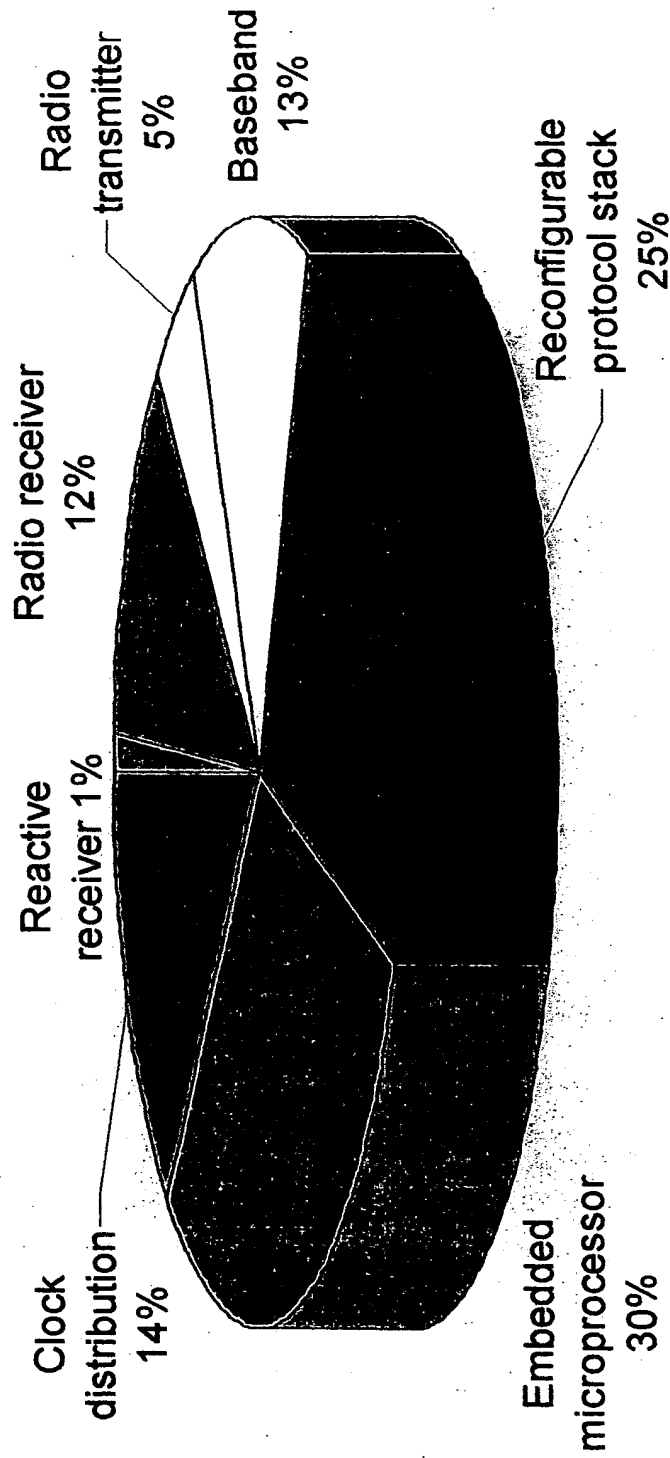


# The Wake-up (Reactive) Radio

- **Always running**
  - Super low power:  
 $10^{-4} \sim 10^{-3}$  active mode power
- **Data radio shut down when idle, and powered up by wake-up radio**
- **Receiver response time: < 10ms**



# *What it Ultimately Boils Down To— Power-Profile of PicoRadio (Projected)*



# Summary/Perspective

- Both the bits/sec/Hz and the bits/nJ quests create formidable energy challenges
- Keep your eyes open for innovative, orthogonal approaches that re-stack the cards
  - There is a whole lot of unexplored land available  $> 10$  GHz
- In the end, it are the laws of physics that provide the ultimate bounds



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